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## Active Control of Nuclear-Enhanced Radiation Belts

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**Introduction:** A high-altitude nuclear detonation by a hostile power could flood the Earth's radiation belts with MeV "killer" electrons, which would remain trapped by the geomagnetic field for years. This orders-of-magnitude enhancement of the normal radiation belts would disable low-Earth-orbit satellites within weeks,[1] thereby degrading military capabilities and severely impacting the economy. This threat has been called a potential "Pearl Harbor in space." Development of an effective countermeasure is a national priority. NRL recognized the importance of this threat early on and initiated a comprehensive 6.1 program in FY04 that includes theory, computer simulation, and laboratory experiment. We are developing quantitative physics models that are needed as a precursor to space-based tests. The ultimate objective is to avoid catastrophic radiation damage to space assets by restoring the radiation belt to its natural state within a week.

**Background:** It has been known since the 1960s that the natural particle population in the radiation belt is controlled by a feedback process: electromagnetic waves are amplified by the "loss-cone" electron distribution naturally present in the radiation belt, and the waves in turn scatter and precipitate particles. There is every reason to believe that the killer nuclear-generated electrons could be similarly precipitated, if it were possible to introduce a sufficiently energetic spectrum of waves with the right wavelength and frequency. Mainline remediation efforts emphasize the use of whistler waves transmitted from a space-based antenna and amplified by the free energy available within the radiation belt. A technical panel in 2001 assessed the available technology and concluded that remediation could be achieved within a week, with only a modest investment of energy from a few satellite-based antennas emitting at 6 kW, if 20 dB amplification of the appropriate waves could be assured. However, while there is clear experimental evidence for sporadic whistler amplification and secondary emission,[2] the circumstances necessary to trigger the process are not well understood or predictable. Nonlinear processes appear to be at work that depend sensitively on the wave frequency, require triggering waves above a threshold strength, and also require the presence of natural magnetospheric inhomogeneities known as ducts. The parametric dependences and scaling laws are unknown. Nor is there any predictive capability for the operation of a high-intensity space-based antenna system within the nonlinear magnetospheric plasma medium. We are currently addressing these issues.

**Current Research:** To understand whistler dynamics in nuclear-enhanced radiation belts, we needed to develop wholly new types of fast numerical simulation models using techniques such as elimination of the displacement current and enforcement of quasi-neutrality. These models have yielded valuable insights. For example, Fig. 4 shows a test that illustrates saturation of whistler amplification by magnetic trapping. The study is now being extended to include inhomogeneities and wave packets of finite size, which lead to de-trapping and, hence, extended amplification and triggered emission. Figure 5 illustrates a full-wave simulation of whistler propagation in ducts with diameter comparable to the whistler wavelength. Earlier ray tracing models are inappropriate for these narrow ducts, which could be self-generated by a large-amplitude whistler, thereby enabling amplification and unattenuated propagation over large distances, even in the absence of natural ducts.

These theoretical investigations of nonlinear whistler optics are complemented by experiments in the NRL Space Chamber. We have investigated the resonance-cone propagation of low-power whistlers and the self-ducting of large-amplitude whistlers to develop the technique for lossless long-distance propagation. Figure 6(a) shows propagation of small-amplitude whistlers in the Space Chamber plasma, illustrating

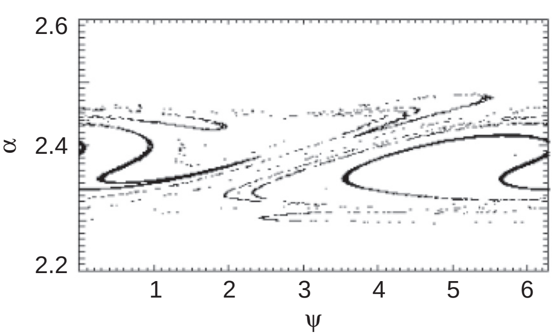


**FIGURE 4**
Computer simulation showing electron density in a 2-D section of phase space (pitch angle $\alpha$ vs electron gyration phase $\Psi$) that illustrates the phenomenon of phase trapping.

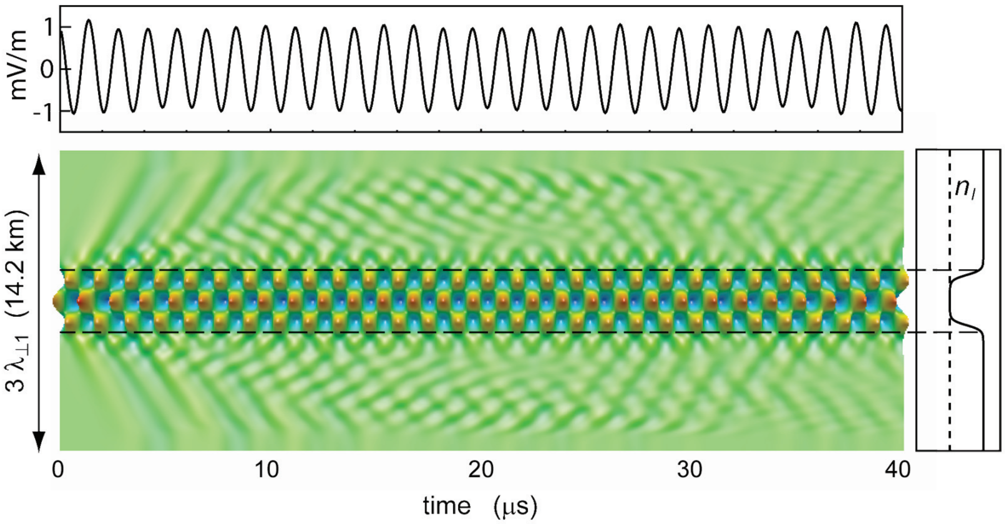


**FIGURE 5**
Computer simulation showing wave ducting within a tube of reduced electron density. The upper curve shows the wave amplitude essentially constant. In the absence of a duct, the wave would expand and thus fall off in amplitude.

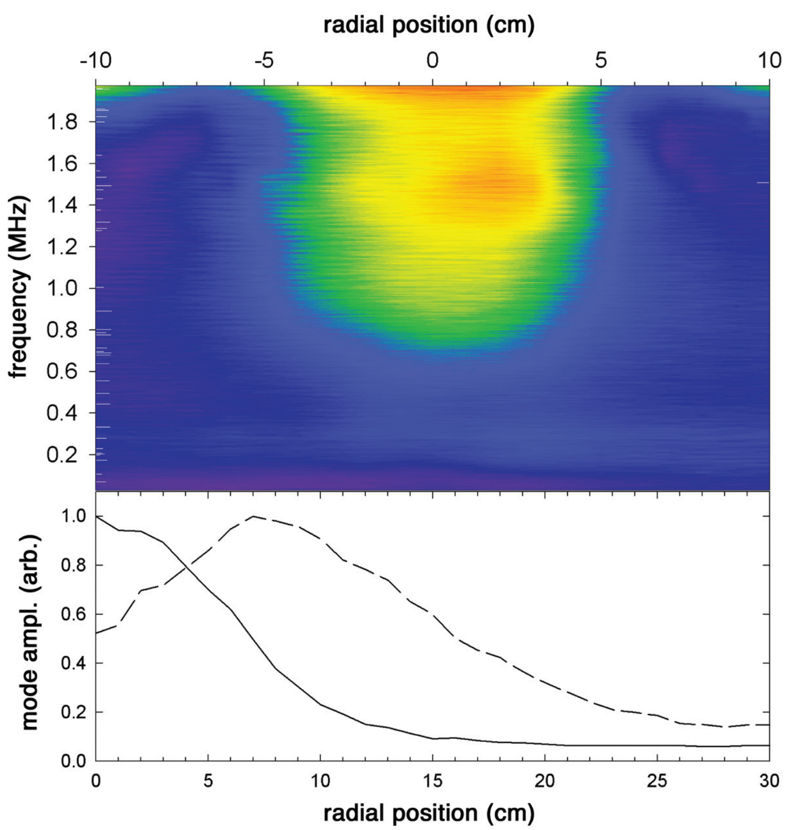


**FIGURE 6**
(a) Experimental measurements of whistler wave resonance cone width as a function of wave frequency. (b) Demonstration of whistler wave self-ducting with transmitting antenna located at $r$ = 0 (solid) and $r$ = 10 cm (dashed).

the low-frequency cutoff at the lower-hybrid resonant frequency and the confinement of wave power within the lower-hybrid resonance cone. Figure 6(b) demonstrates the self-ducting of high-power whistler waves. The data show collimation of the whistler radiation pattern two meters downstream, with the transmitting antenna located on the chamber axis (solid line) and 10 cm off axis (dashed line).

**A New Remediation Concept:** We are also developing a radically different approach for rapid remediation based on massive injection of energy over a short duration. If a large quantity of neutral vapor such as lithium is released from a satellite moving in the equatorial plane, the vapor is photo-ionized over a period of about an hour. The resulting ions, moving at ~7 km/s normal to the geomagnetic field, spin up into a highly unstable "ring" distribution, which emits large amplitude electromagnetic waves in the desired frequency and wavelength range. These waves can precipitate the killer electrons within hours, as opposed to a week. The process in effect taps the orbital kinetic energy to create a giant ion magnetron in the radiation belt. A ton of neutral lithium would carry 10 GJ of energy, vastly more than could ever be introduced through electromagnetic antennas.

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[1] D.G. Dupont, "Nuclear Explosions in Orbit," *Sci Am.* **290**(6), 100, 2004.

[2] R.A. Helliwell, "VLF Wave Stimulation Experiments in the Magnetosphere from Siple Station, Antarctica," *Rev. Geophys.* **26**, 551, 1988.

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